Bent crystal-assisted Beam manipulations

A wide panorama: SHERPA and UA9

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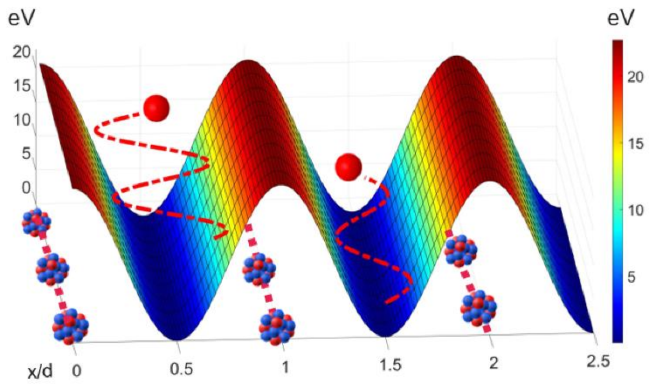
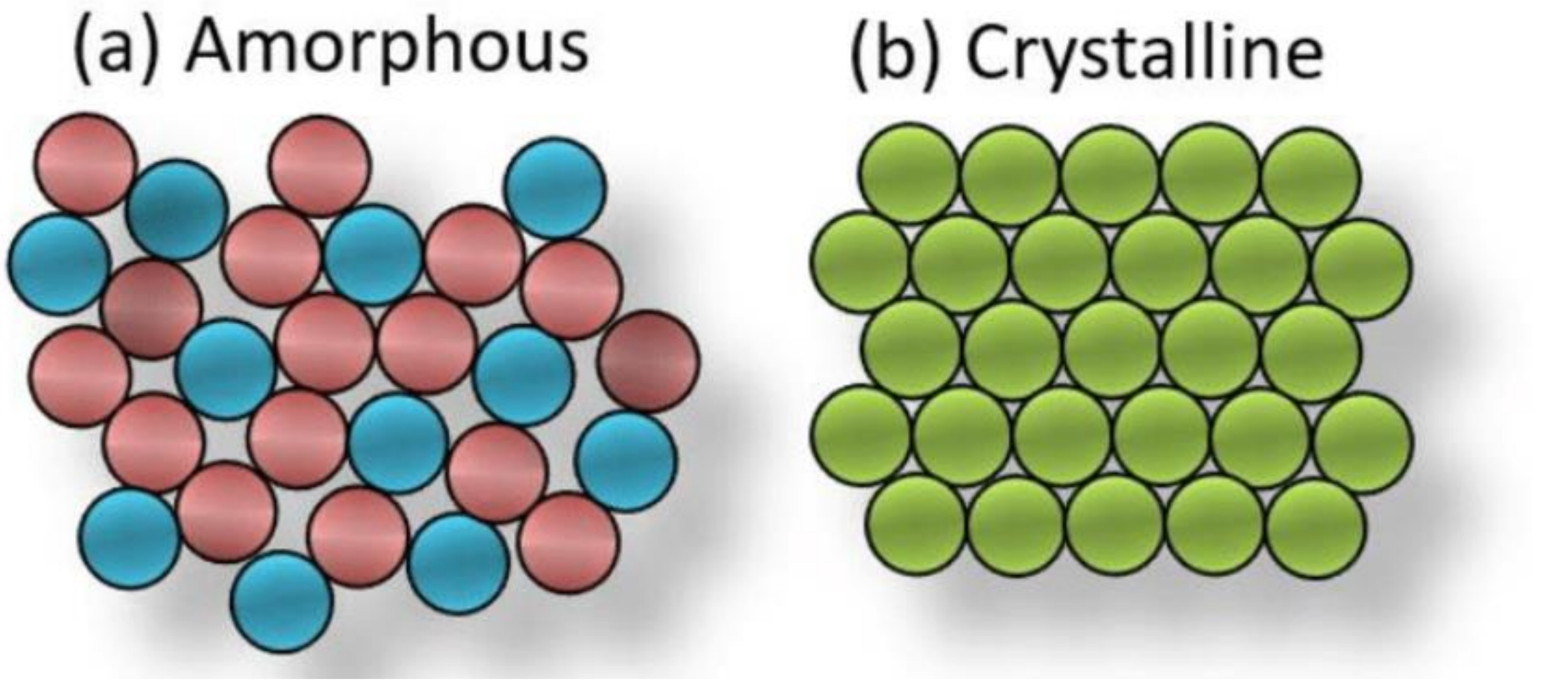
Ph.D. Seminars series
31/05/2023 – Aula Conversi

1 Introduction to Crystal Channeling



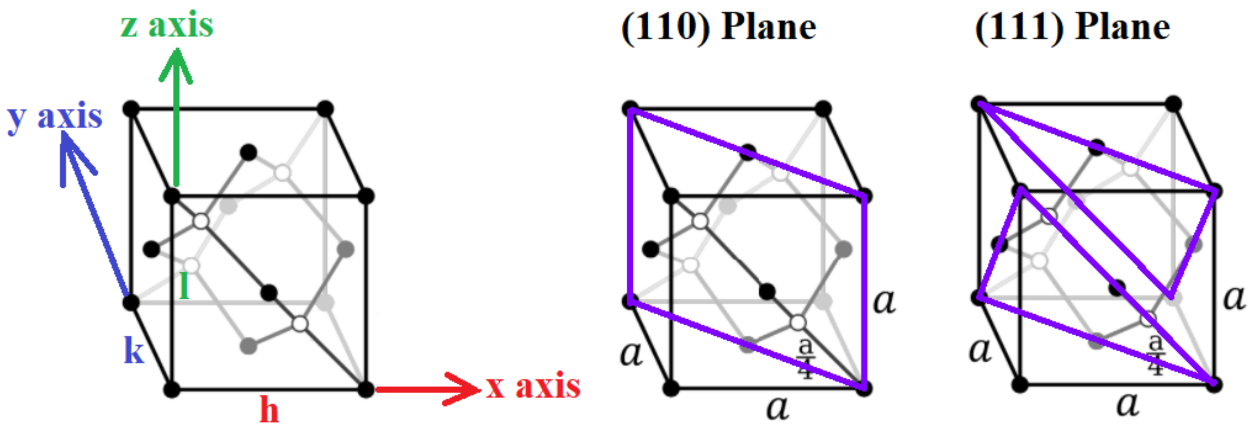
Crystalline vs Amorphous matter

- ➢Crystalline solids: Ordered atomic structure
- ➢Amorphous solids: Not-ordered atomic structure



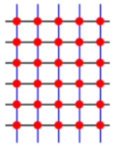
Crystals characterization

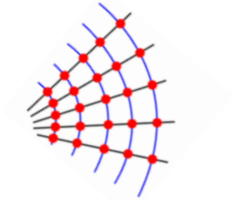
- Ordered disposition of atoms in a crystalline lattice (called also Bravais Lattices)
- Miller Indices (h, k, l) define a plane family
- In Silicon, the lattice is a Face Centered Cubic with Basis
  - Basis atoms shifted inward by ¼ along the length of the bulk diagonal

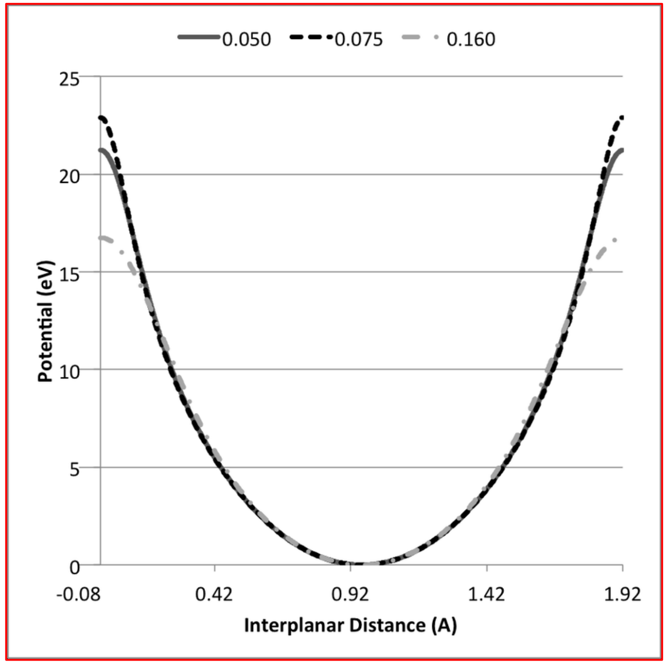


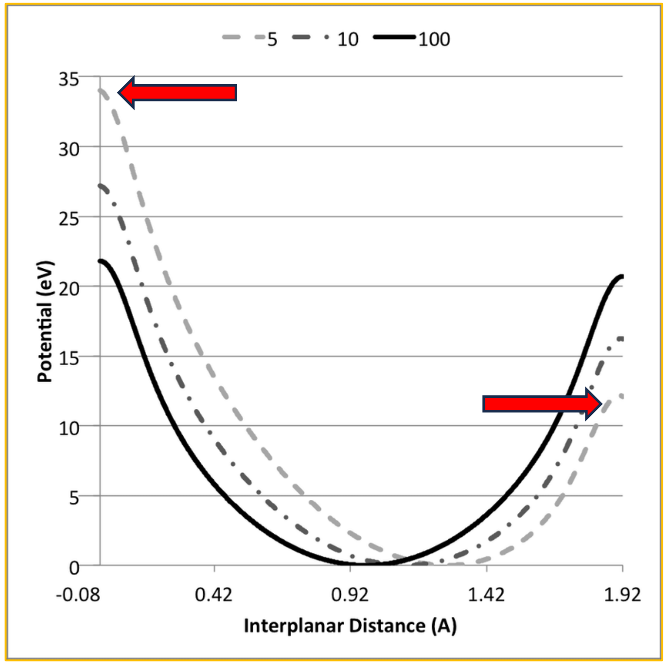
Interplanar Crystal Potential

- Periodicity of the structure → Periodicity of the potential

- If the crystal is straigth  
  - Periodic potential without perturbations

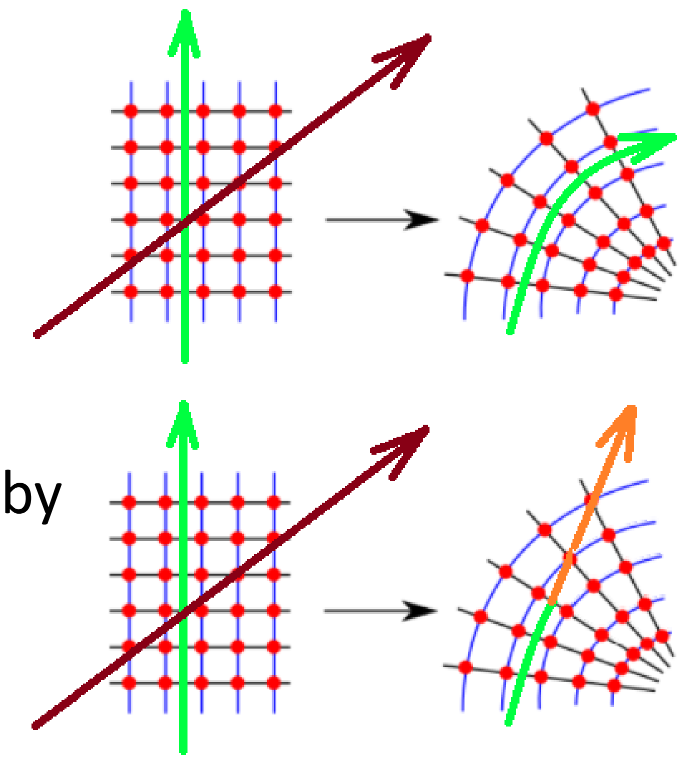
- If the crystal is bent  
  - Stress-Induced deformation in a controlled way
  - Centrifugal Repulsion effect

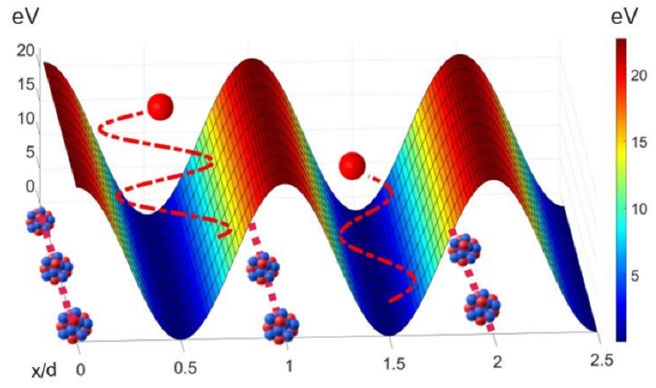




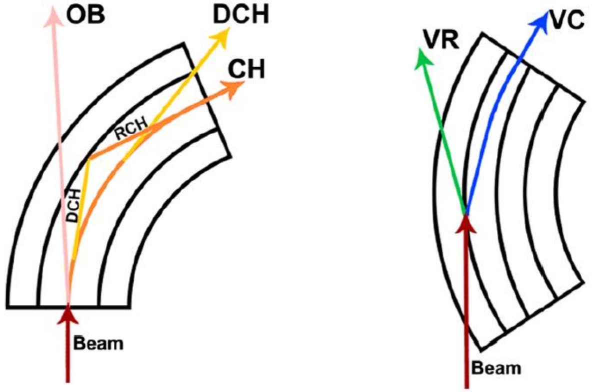
Crystal Channeling

- A particle impinging on a crystal can behave differently depending on its alignement with the crystal.
  - Amorphous/Coherent Behaviour
- If aligned with the crystal planes, the particle can be trapped by the interplanar potential, following a path constrained by the minima of this potential
- This effect is known as Channeling
- If the crystal is bent, the particle will follow the crystal plane bending
  - This effect has been used to bend particle beams using bent crystals
- If the particle leaves the Channeling condition, the effect is known as Dechanneling



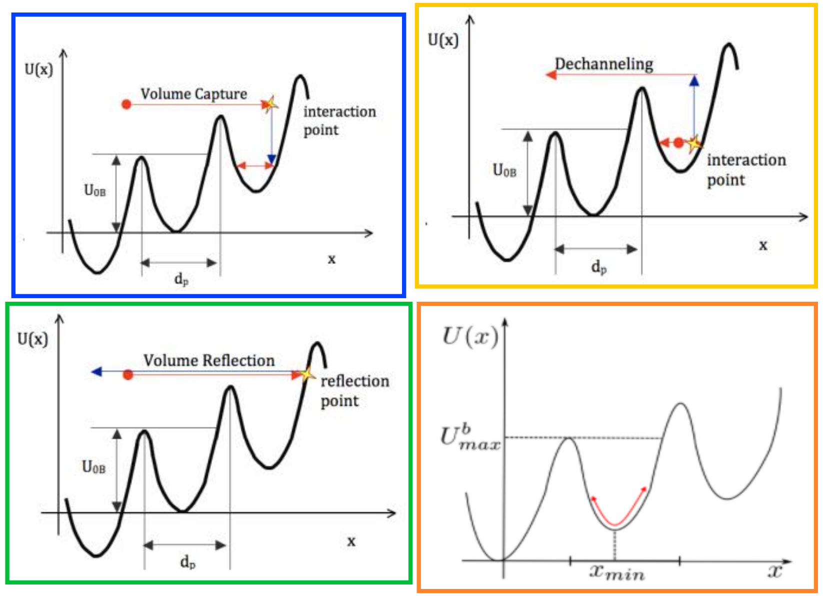


Coherent Processes in Bent Crystals



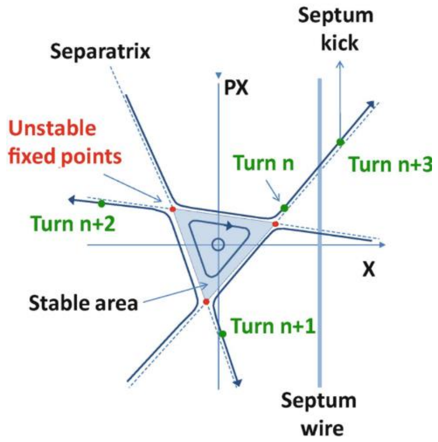
- Channeling (CH)
  - Critical Angle $\theta_c = \sqrt{2U/E}$
  - Charghed particles entering with $\theta < \theta_c$ can undergo Channeling

- Dechanneling (DCH) – Volume Capture (VC) – Rechanneling (RCH)
  - No more CH condition: DCH can happen (sometimes followed by RCH)
  - RCH is observed only with negative particles



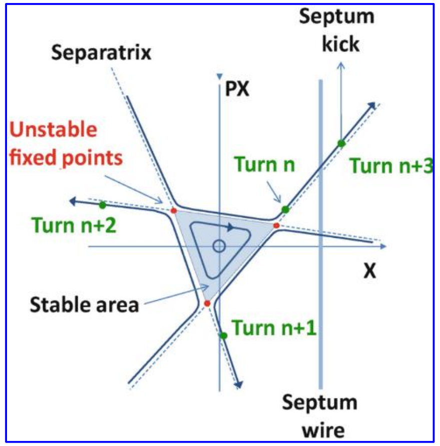
- Volume Reflection (VR)
  - Charghed particles reflected by the crystal potential barrier

2 Beam Extraction



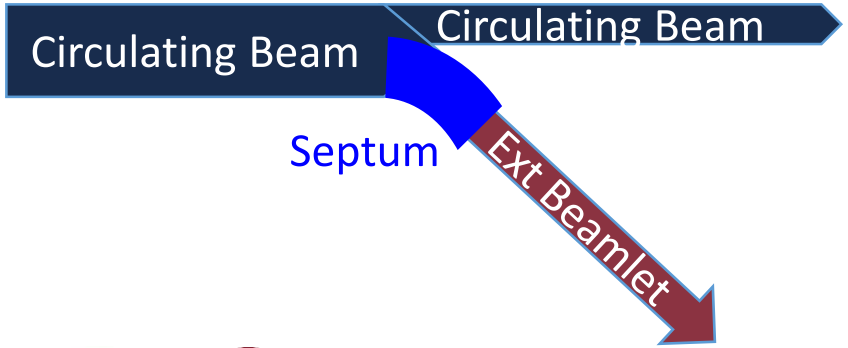
Resonant Beam Extraction

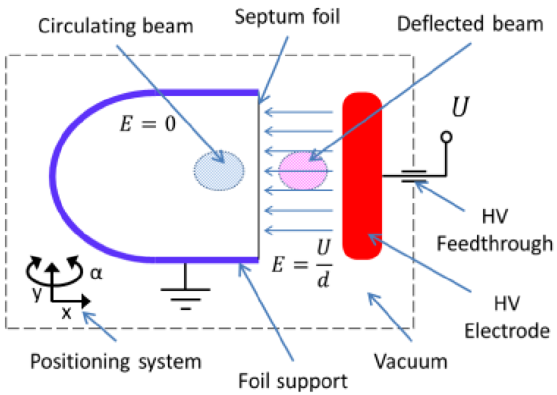
- Standard technique consists in the Resonant extraction
  - $nQ_x + mQ_y = k$ (n, m, k integer) → Resonance condition
  - The Beam core (particles circulating on the nominal beam trajectory) is not perturbed and particles remain on trajectory
  - Part of the beam halo that enters the region where $\mathrm{E} \neq 0$ (electrostatic septum) or $\mathrm{B} \neq 0$ (magnetic septum) is deflected away and thus can be extracted

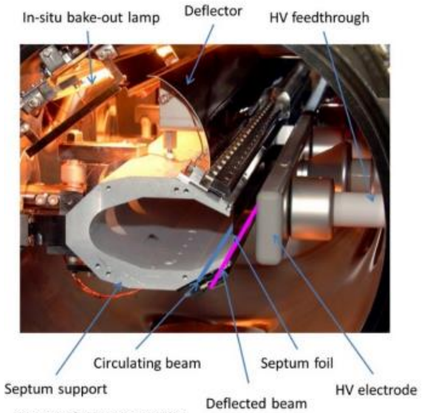


See Backup Slides

Tune = Number of Betatron Oscillations performed by a particle in one turn





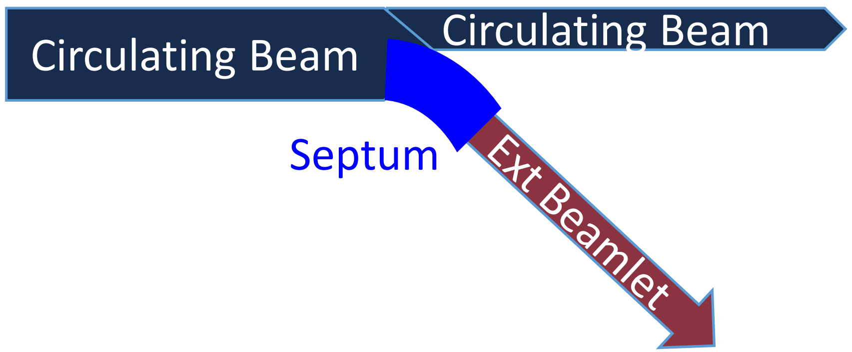


Courtesy of CERN Septa Section

Resonant Beam Extraction disadvantages

- Operating an accelerator near resonance is a risk if not done properly
  - Resonances can lead to beam instability if not correctly compensated afterward

- Risks: The septum is very close to the circulating beam design orbit
  - If a powerful beam (i.e. MW of power) impacts on the septum, it is possible that the septum itself can overheat and/or eventually melt
  - If there is a malfunction on the magnets just before the septum it is possible to have beam loss
  - Require strong pulsed Kicker magnets several meters before the septum



Non-Resonant Beam Extraction

- Also Non Resonant beam extraction techniques relies on septa magnets but does not require Kicker magnets
  - The beam separation is not induced by a resonance but by an element of the accelerator
  - Crystal-Assisted beam extraction → Slow non-resonant methodology currently under study
  - Single-turn or multi-turn extraction

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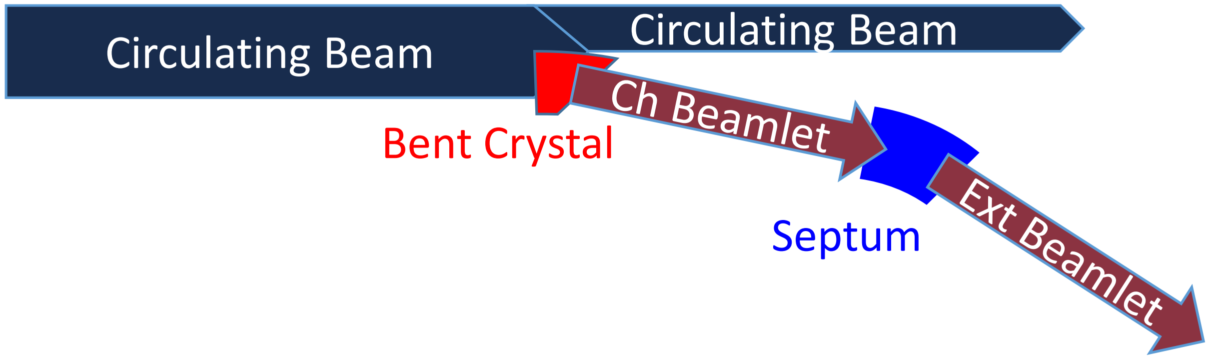
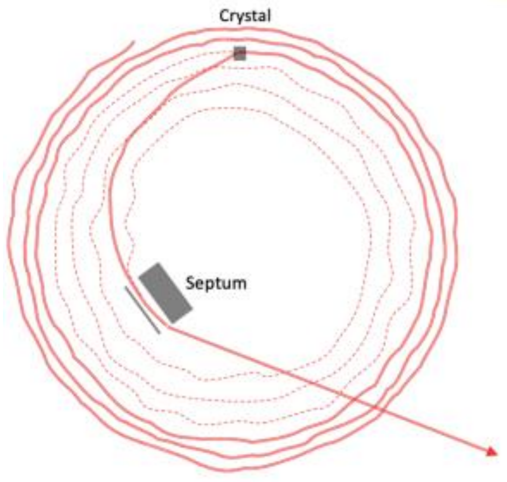
Phys. Rev. Accel. Beams **25**, 033501





Extracted beam at INFN LNF

- ~60 m long S-Band 2856 MHz LINAC providing 500/800 MeV e^+/e^-
  - It provides only 50 Hz bunches of 300 ns maximum length (Duty Cycle 10^{-5})
- DAΦNE e^+/e^- collider length $\sim 100\ m$. $E_{cm} \sim 1\ GeV$ (Φ-Factory)
- Poseydon Project – Continuous extracted beam – ArXiv:1711.06877
  - Converting DAΦNE into a pulse-stretcher and a Storage Ring Facility to obtain an almost continuous extracted beam for users
  - Resonant or Crystal-Assisted extraction? Can we use crystals?
- Sherpa Project (Slow High-Efficiency Extraction From Ring Positron Accelerator)
  - Prove the feasibility of 1 mrad deflection

  With bent crystals

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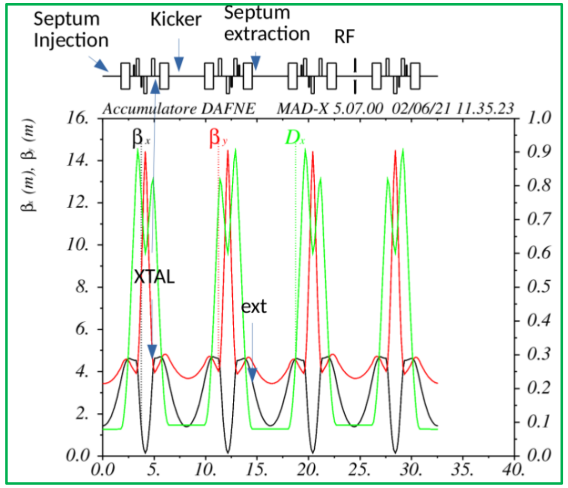
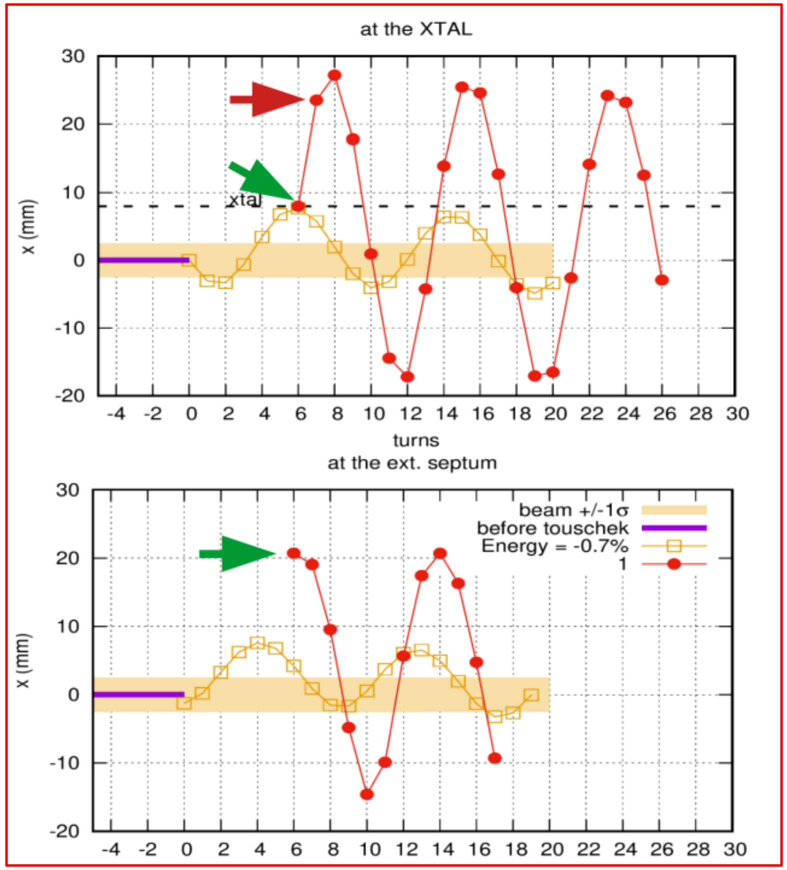
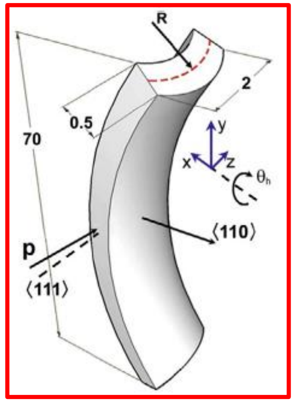
Phys. Rev. Accel. Beams **25**, 033501

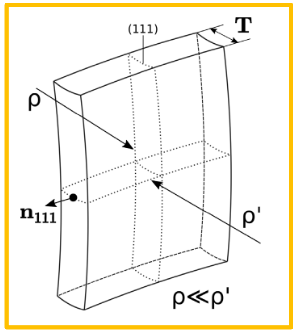




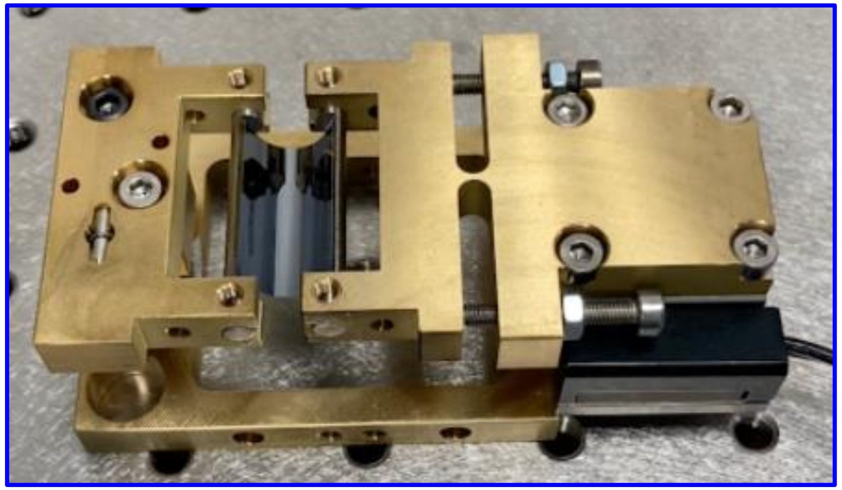
- Damping Ring / DAΦNE extraction under study

The SHERPA Project: Bent Crystal





- In order to bend the crystal an holder must be used
- Anticlastic and Quasi-Mosaic deformation
  - (110) plane: Anticlastic bending (induced by Anticlastic deformation)
  - (111) plane: Quasi-Mosaic bending (induced by Quasi-Mosaic deformation)
- Specifically designed in order to achieve $\sim 1\ mrad$ channeling angle
  - $\sim 15\ \mu m$ Thickness
  - $\sim 1.5\ cm$ Bending Radius
- Crystal similar to the one used at MAMI by INFN-Fe group for e^-
  - PhysRevLett.112.135503 (Mazzolari et al)



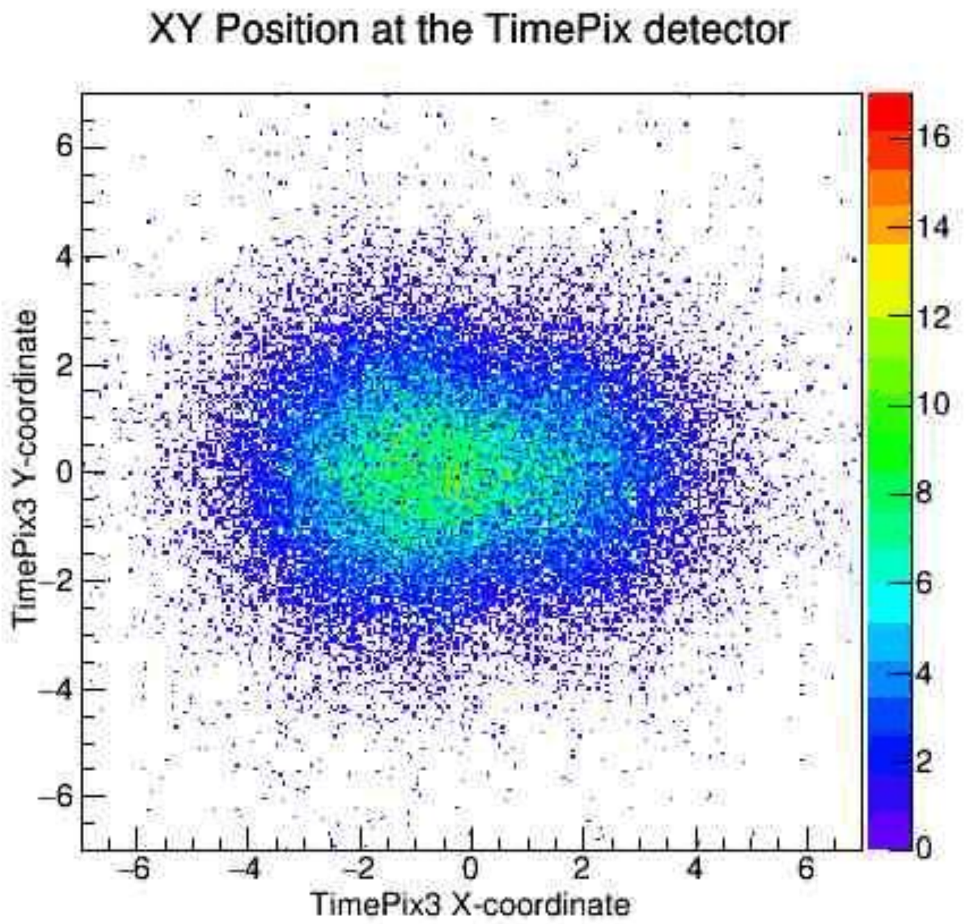
Crystal Alignment and Angular Scan

See Backup Slides

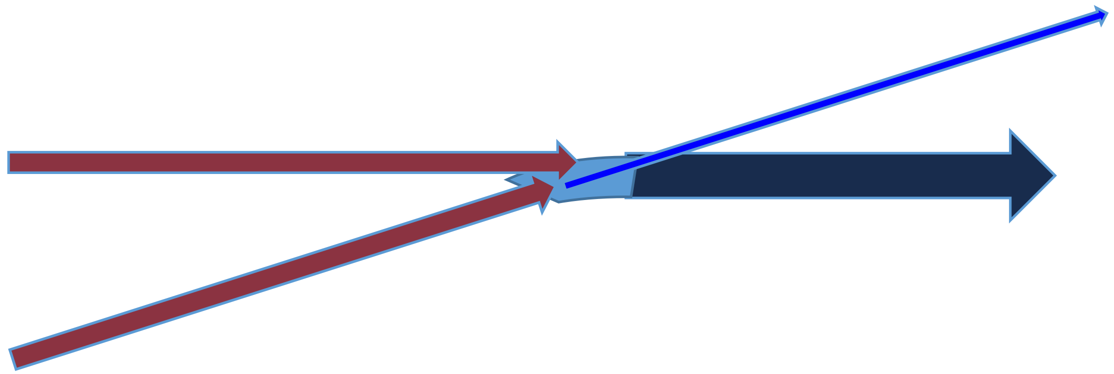
- Several simulations performed to study the reliability of the Geant4 Channeling Routine
  - 400 GeV protons at H8
  - MAMI e^+, e^- 855 MeV
  - SHERPA e^+, e^- 511 MeV

- The beam spot distribution at the Si TPX3 detector has been simulated
  - The spot should be $\sigma(x) \times \sigma(y) = (0.5 \times 0.5)\ mm^2$
  - The divergence should be $\sigma'(x) = 500\ \mu rad$ and $\sigma'(y) = 300\ \mu rad$

- Preliminary tests of the SHERPA TPX3 detector imaging at LNF BTF have been carried out

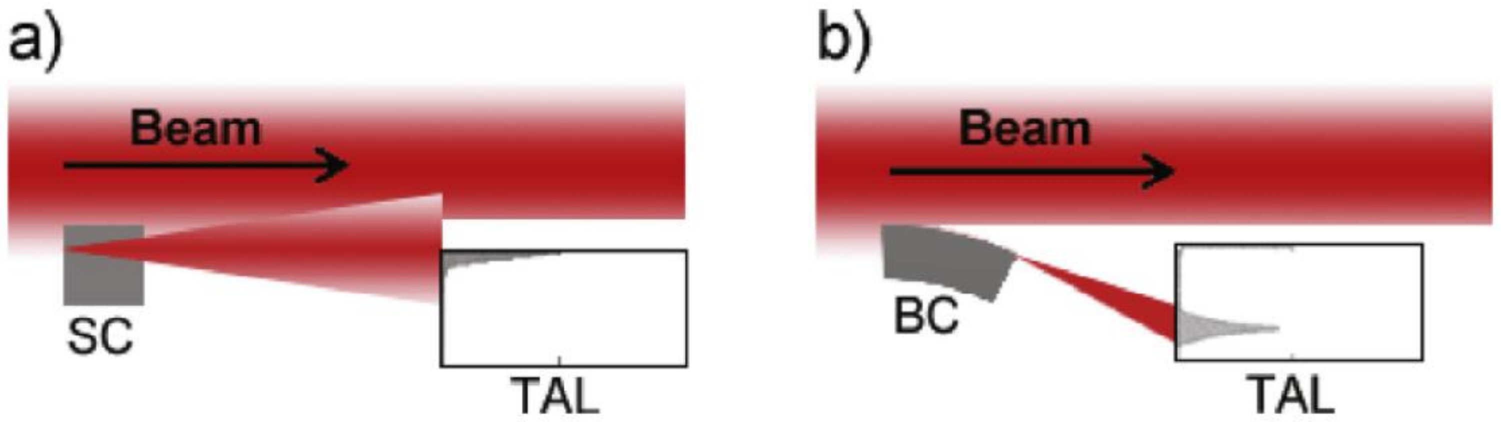


3 Beam Collimation and Coalescence

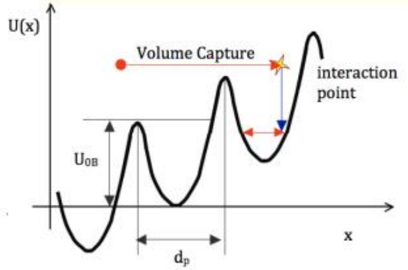


Crystal Assisted Beam Collimation

- ➢Crystal-Assisted beam collimation is conceptually similar to beam extraction, but the beam is deflected toward a Heavy Metal Absorber (High-Z material like W) using a crystal
  - ➢If a collimator (SC) is placed directly on the beam halo→the Secondaries produced after the Hadronic Shower can interact with the circulating beam
  - ➢With Crystal-Assisted collimation is possible to avoid most of the On-Axis Secondaries

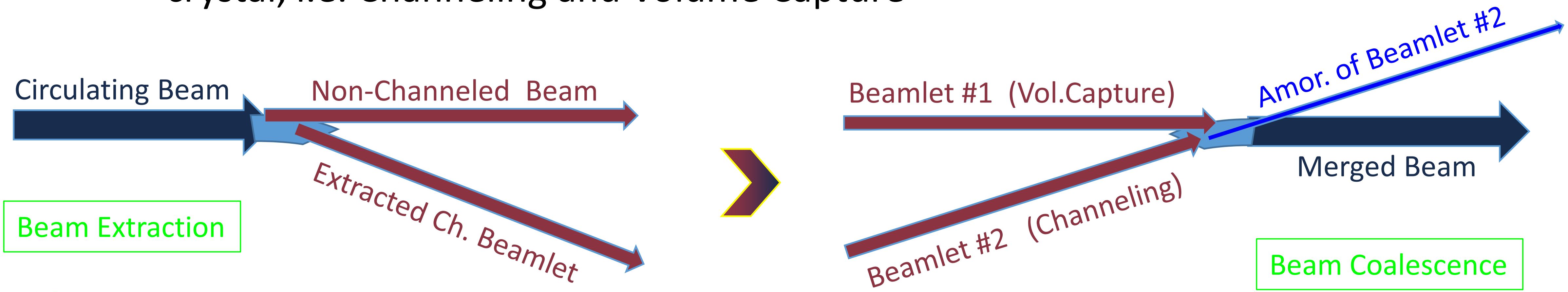


Reminder on VC



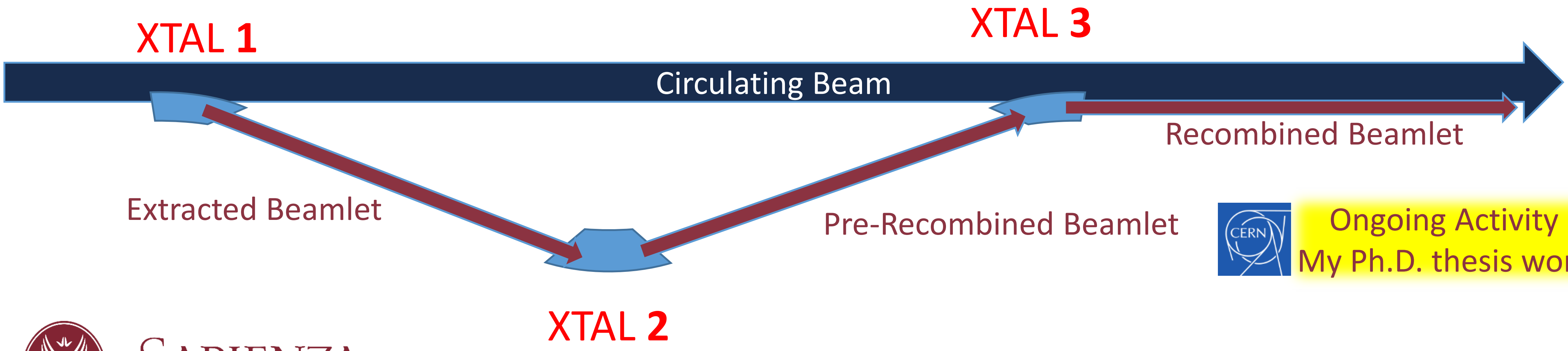
Beam Coalescence

- It is possible to use the Channeling effect to merge beams coming from different directions
  - This process is the «dual» of the beam extraction
  - Beam Extraction: A beamlet is extracted from the halo of the circulating beam
  - Beam Coalescence: Two beams are merged using coherent processes in a bent crystal, i.e. Channeling and Volume Capture



Beam Coalescence – UA9/Config 1 at CERN

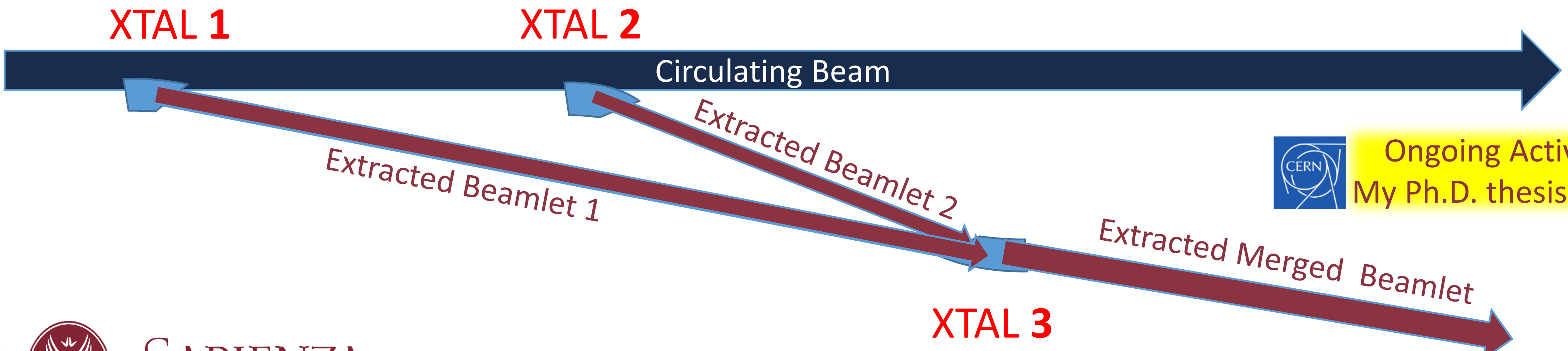
- UA9 Setup under test at CERN – June 2023
  - A Beamlet is extracted from the main circulating beam using a crystal XTAL1 oriented in Channeling
  - The beamlet passes through XTAL2 oriented in Channeling
  - Subsequently, the beamlet is Volume-Captured by XTAL3 and thus is recombined to the circulating beam



Ongoing Activity
My Ph.D. thesis work

Beam Coalescence – UA9/Config 2 at CERN

- UA9 Setup under test at CERN – September 2023
  - A Beamlet (1) is extracted from the main circulating beam using a crystal XTAL1 oriented in Channeling
  - Another Beamlet (2) is extracted using XTAL2 oriented in Channeling
  - Subsequently, the beamlet (2) is Volume-Captured by XTAL3 and thus is recombined to the beamlet (1). The extracted beam exits in the direction of B1



Ongoing Activity
My Ph.D. thesis work

4 Conclusions

Take-Home messages

- Bent Crystsal-Assisted beam extraction and coalescence are novel techniques currently under study
  - Beam Merging with crystals must be performed in an appropriate way
  - The Phasespace of the two impinging beamlets must be matched as possible otherwise the beam will degrade due to filamentation
- Bent Crystsal-Assisted beam collimation is nowadays widely used at CERN
- It will be possible to implement those setups in accelerators such as FCC or Muon Collider
  - *Stay tuned! I will present my further results time by time ;)*

- I sincerely Acknoweledge the INFN Roma & INFN LNF that allowed me to perform all the necessary activity to develop this presentation
  - Many Thanks to Paolo Valente, Mauro Raggi, Marco Garattini, Alessandro Variola, Paola Gianotti, Luca Foggetta and the BTF Staff

- I will be involved in Some important Test-Beam at CERN within the UA9 Collaboration
  - Many Thanks to Walter Scandale, the UA9 Collaboration and the CERN Staff

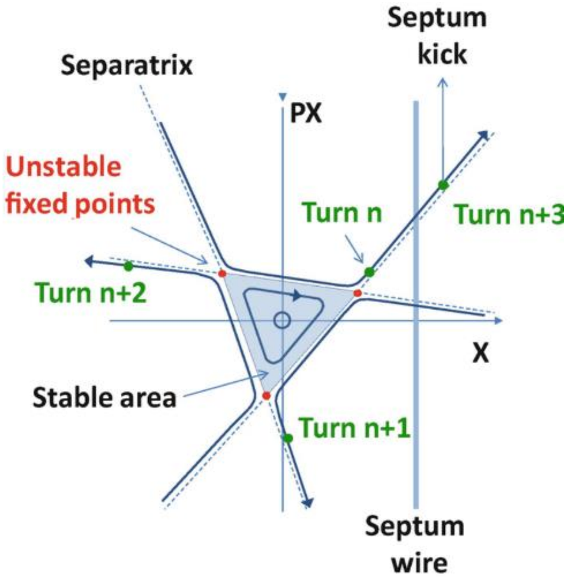
Now this is not the end

It is not even the Beginning of the End

But it is, perhaps, the End of the Beginning

- W.Churchill 10 Nov 1942

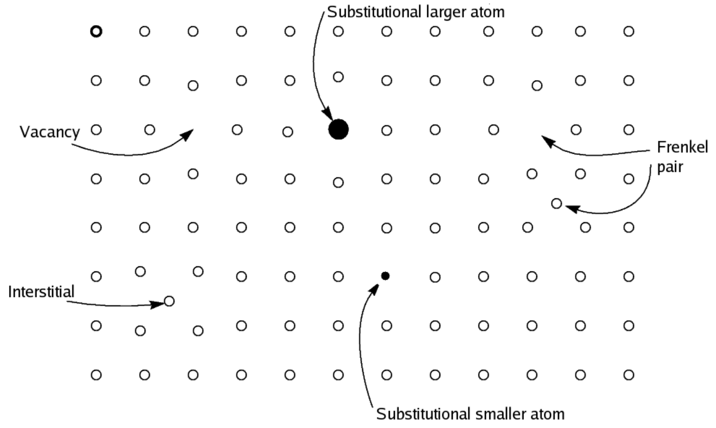
Many Thanks for Your Attention!
Questions? Comments? Remarks?



A Backup Slides

Backup

Crystal Imperfection



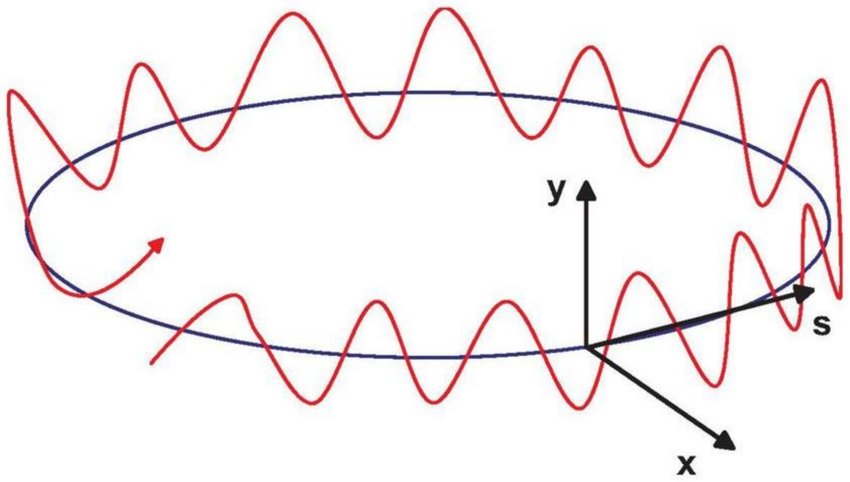
- Assumption: **Crystals are perfect**
  - No Dislocations/Vacancies/Irregularity
- But the reality is different
  - Crystal production is not perfect
  - Stress induced during crystal cooldown and further manipulation (cut, maching, …) can lead to lattice irregularities
  - Irregularities and imperfections lead to an uncontrolled potential well perturbation so it is possible that particles lose channeling conditions, i.e. by inelastic collision on «extra atoms»

Backup

Resonance in Circular Accelerators

- Resonance Condition → $nQ_x + mQ_y = k$ (n, m, k integer)
- $p = |n| + |m|$ is the resonance order
- Introduce the machine TUNE (horizontal & vertical)
  - Tune = Number of Betatron Oscillations performed by a particle in one turn

schematic of betatron oscillation around storage ring

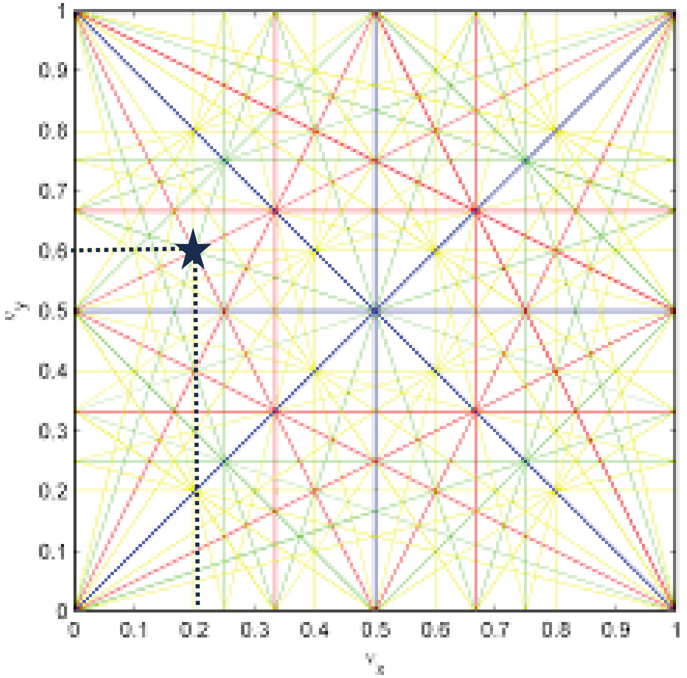


Backup

Resonance in Circular Accelerators

- Resonance Condition → $nQ_x + mQ_y = k$ $(n, m, k$ integer)
- $p = |n| + |m|$ is the resonance order
- Introduce the machine TUNE (horizontal & vertical)
  - Tune = Number of Betatron Oscillations performed by a particle in one turn
  - i.e. $Q_x = 35.2$ and $Q_y = 59.6$ means that *in one turn* the particle performs:
    - 35 total oscillation + a fraction of oscillation equal to 0.2 in the X plane
    - 59 total oscillation + a fraction of oscillation equal to 0.6 in the Y plane
    - Let $n = 2$ and $m = 1 \rightarrow \mathrm{k} = 2 * 35.2 + 1 * 59.6 = 130$
    - Considering the tune non-integer part only → $\mathrm{k} = 2 * 0.2 + 1 * 0.6 = 1$
    - $p = |n| + |m| = 3 \rightarrow$ **Third order Resonance**

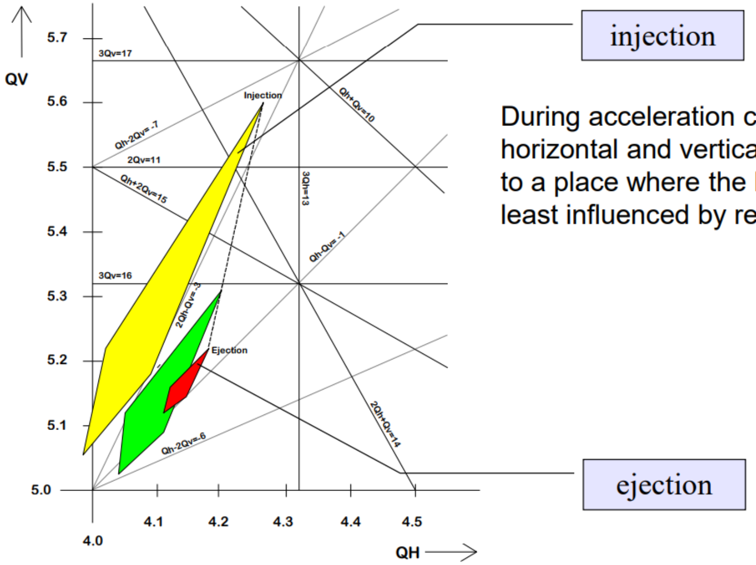
juas
Joint Universities Accelerator School



Resonance in Circular Accelerators

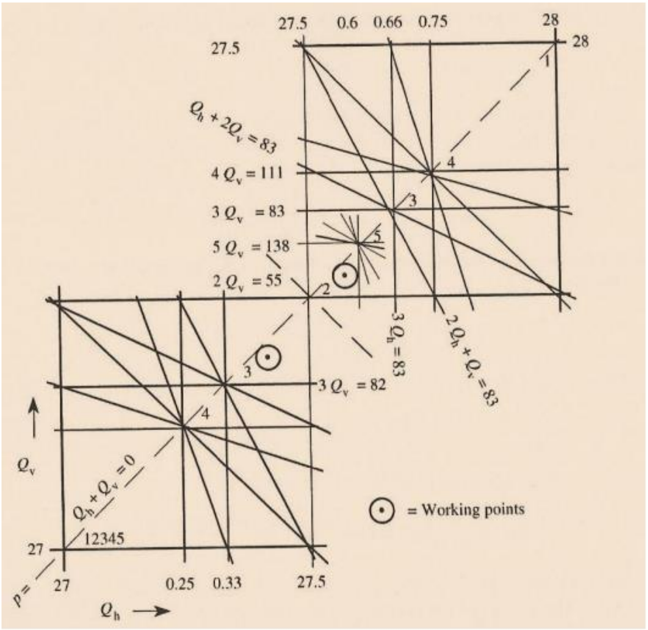
- Operating the accelerator near resonances can lead to beam loss due to uncontrolled and unbalanced amplitude increase
- Have a look to some CERN machines operational ranges

P.S. Booster Tune Diagramme



During acceleration change the horizontal and vertical tune to a place where the beam is least influenced by resonances.

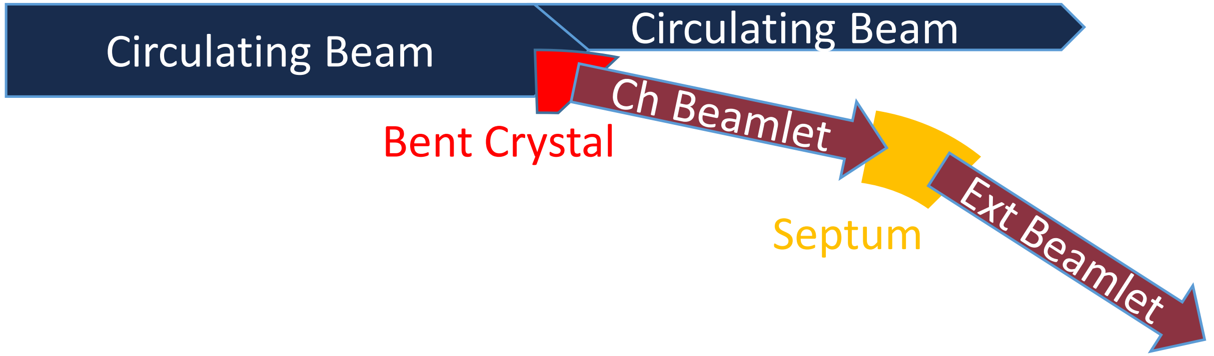
Homework for the operateurs: find a nice place for the tune where against all probability the beam will survive



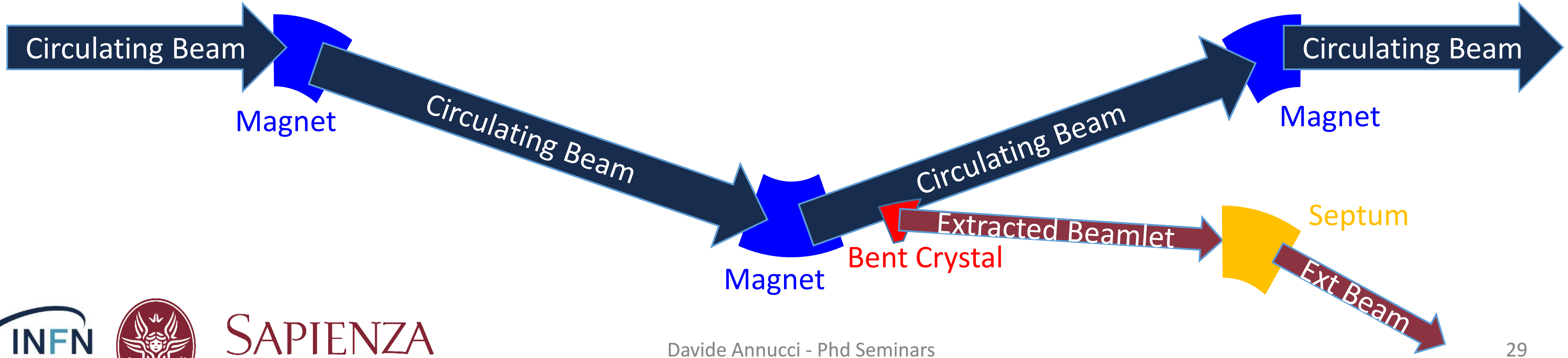
SPS Working Diagramme

Non-Resonant Beam Extraction

- Direct Extraction or Closed-Orbit Bump scheme
  - Direct extraction

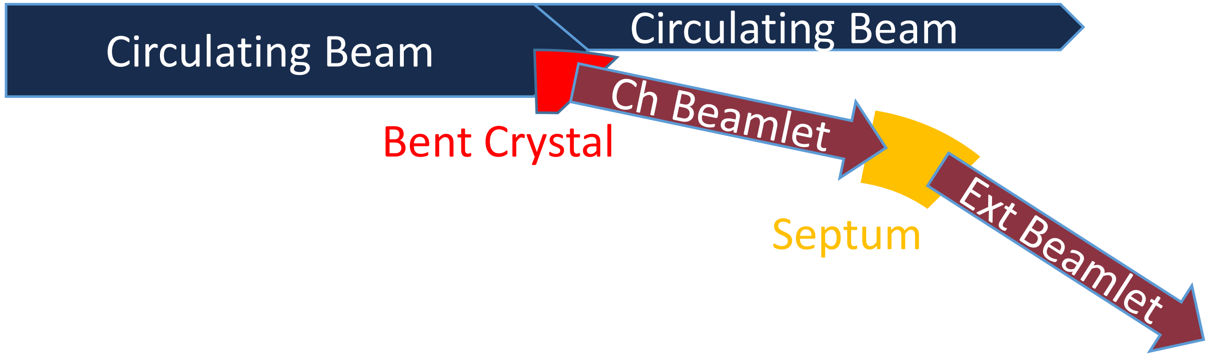


  - Closed Orbit Bump

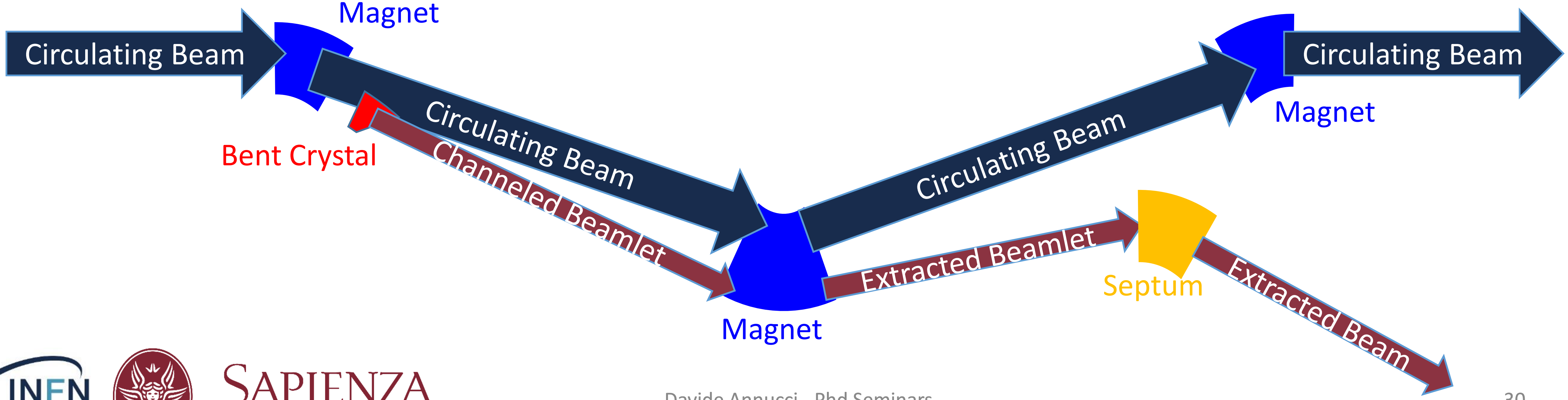


Non-Resonant Beam Extraction

- Direct Extraction or Closed-Orbit Bump scheme
  - Direct extraction



  - Closed Orbit Bump



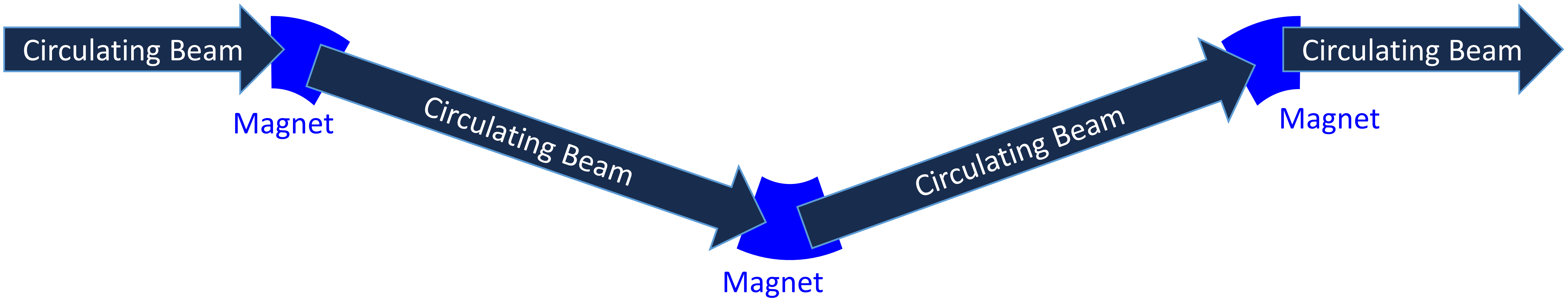
Non-Resonant Beam Extraction

- An alternative to the Direct Extraction scheme is the so called Closed-Orbit bump Scheme
- Let's learn how to build this extraction setup

- All starts with the circulating beam on its unperturbed design orbit

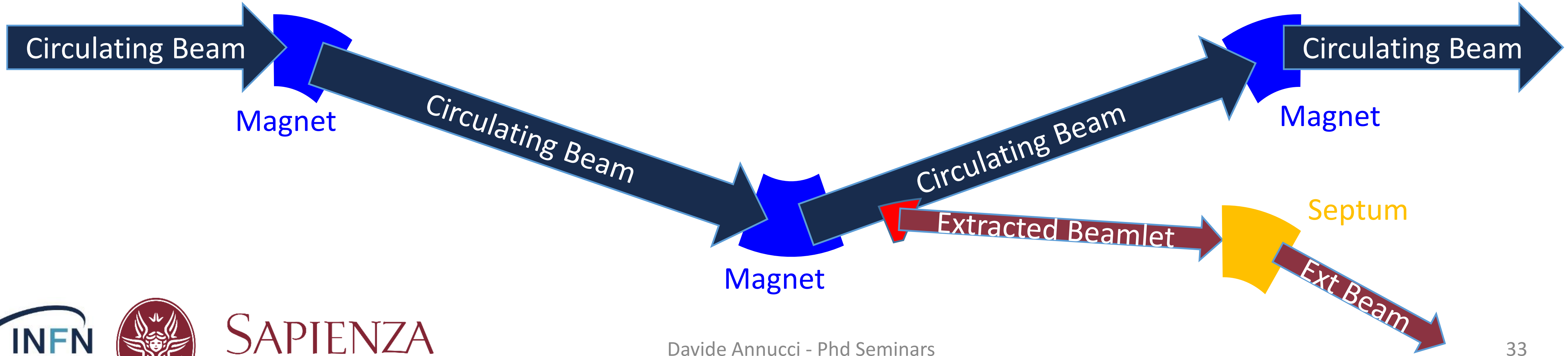
Non-Resonant Beam Extraction

- Add some magnets to induce a zig-zag beam trajectory
- This is called a 3-Magnets closed-orbit bump
- The beam travels for longer path and the Dispersions increases. This is due to the dipole magnets action that enhance $\Delta P/P$

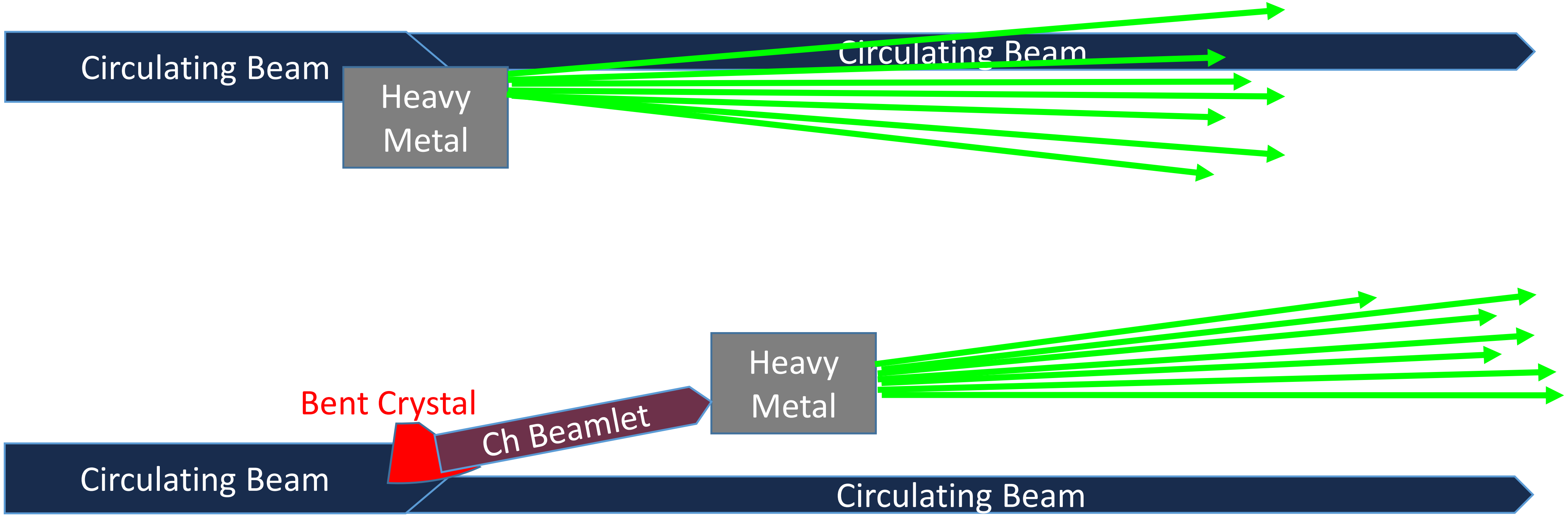


Non-Resonant Beam Extraction

- Add a Bent Crystal just after the second magnet
- If the crystal is placed correctly, the *Halo of the circulating beam* will undergo Channeling and thus the extracted beamlet can be further separated using the Septum Magnet
- The circulating beam core is untouched



Crystal Assisted Beam Collimation



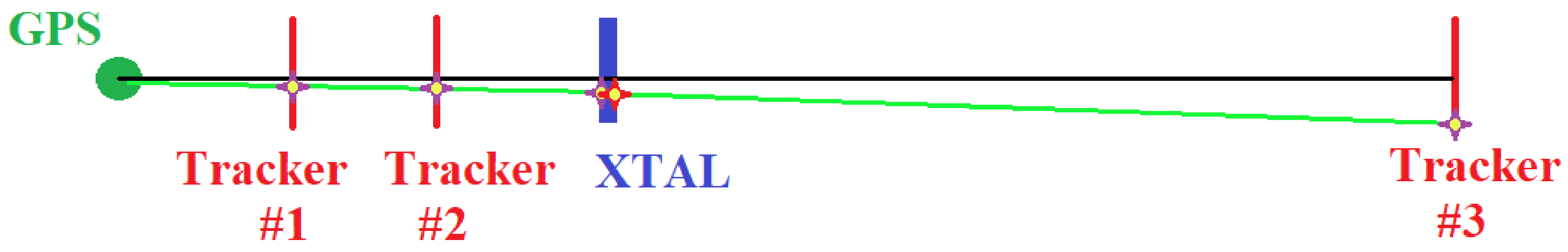
B SHERPA Simulations / Profiles

My Master Thesis

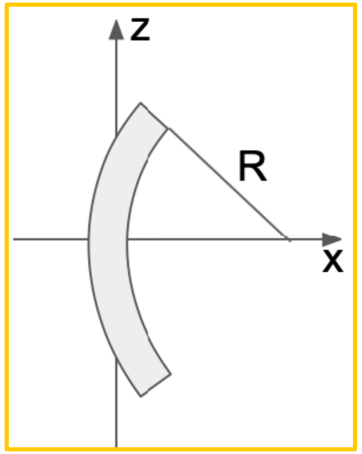
Backup

Geant4 Simulations structure

- AngXin, AngYin, PosXin, PosYin, AngXout, AngYout, AngCry

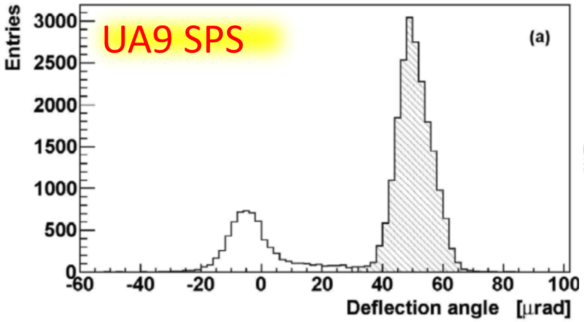


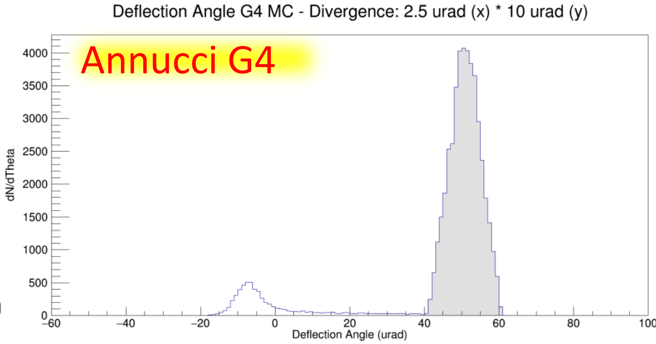
- T1 and T2 used to compute AngXin and AngYin because GPS has spot and divergence $\sigma(x), \sigma(y), \sigma'(x), \sigma'(y) \neq 0$
- Track impinges on XTAL, giving PosXin and PosYin
- Bending is simulated
- Particle outgo XTAL at known position and with known direction, then it proceede straigth until T3
- T3 and XTAL used to evaluate AngXout, AngYout
- AngCry describes XTAL orientation



Geant4 Simulations

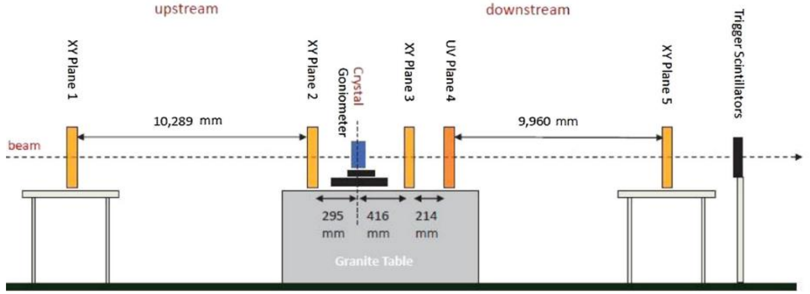
- G4 Cannelling Example implemented only in version 10.05.p01
  - G4 Routine described in http://arxiv.org/abs/1403.5819 by Enrico Bagli et al.
  - No Rechanneling implemented, but considered *«a posteriori»*
  - Channeling, Dechanneling, Volume Capture and Volume Reflection implemented
  - The only lattice plane available is the (110)
  - Beam and crystal parameter and orientation modified by Data Cards
- G4 output variables distributions are the TRUE variable distributions
  - Impinging/outgoing X/Y-angle and impinging/outgoing X-position
- An intense work has been done in order to validate and cross-check the G4 routine. (reported SPS 400 GeV proton H8 UA9, by Scandale/Taratin)
  - Also MAMI setup with e- gives compatible results with Geant4 simulations

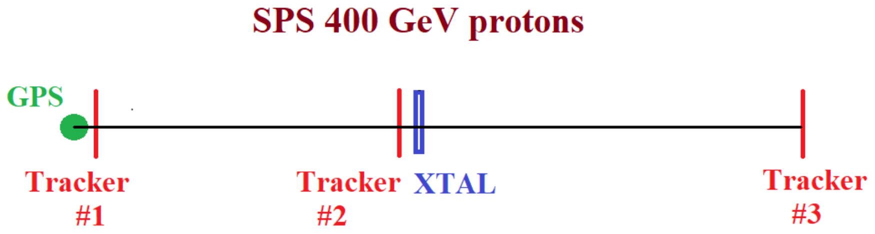


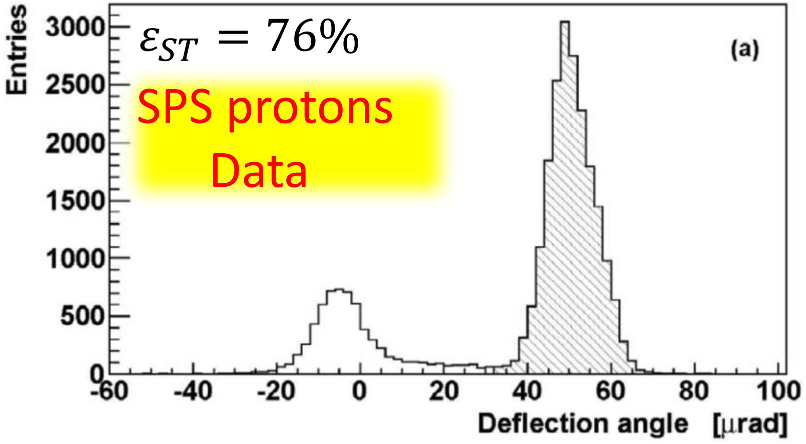


Geant4 H8 SPS Simulations

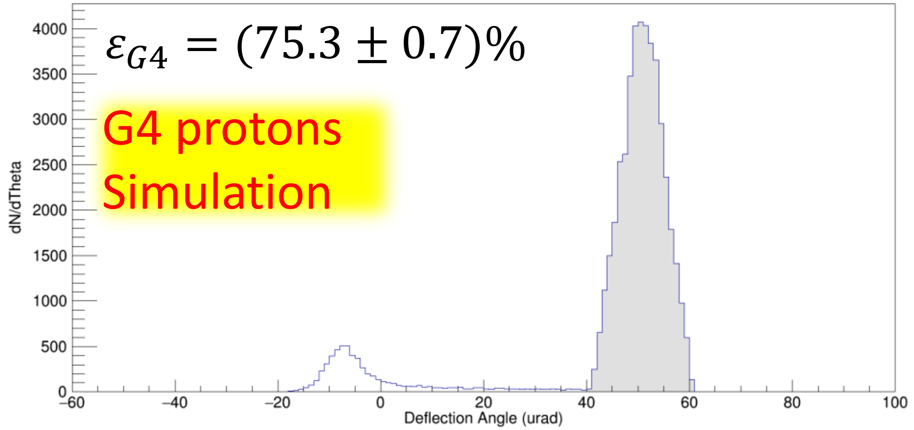
- SPS 400 GeV proton H8 UA9 setup described in Physics Reports, Volume 815, 25 June 2019, Pages 1-107 (Scandale/Taratin)
  - Angular cut (SPS) $|\theta_x|, |\theta_y| < 5\mu rad$. In G4, $\sigma'(x) = 2.5\mu rad$







Deflection Angle G4 MC - Divergence: 2.5 urad (x) * 10 urad (y)



Geant4 MAMI Simulations

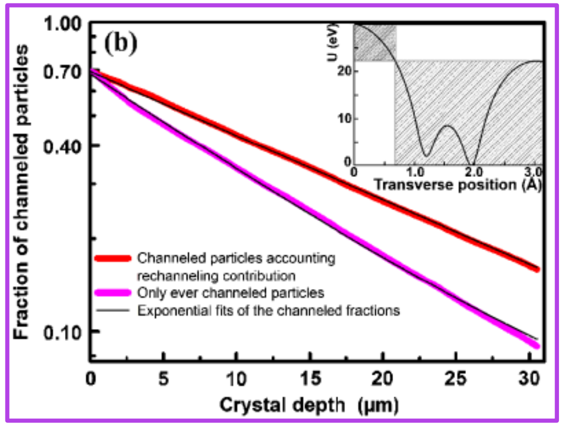
- MAMI setup described in PhysRevLett.112.135503 (Mazzolari et al)
- Angular Scan: the crystal is rotated wrt impinging beam
  - MAMI data collected with (111) plane; G4 Simulations carried on (110) plane
  - $\varepsilon_{G4} = (14.6 \pm 1.3)\%$; without Rech; but 50%particles recycled through Rechanneling

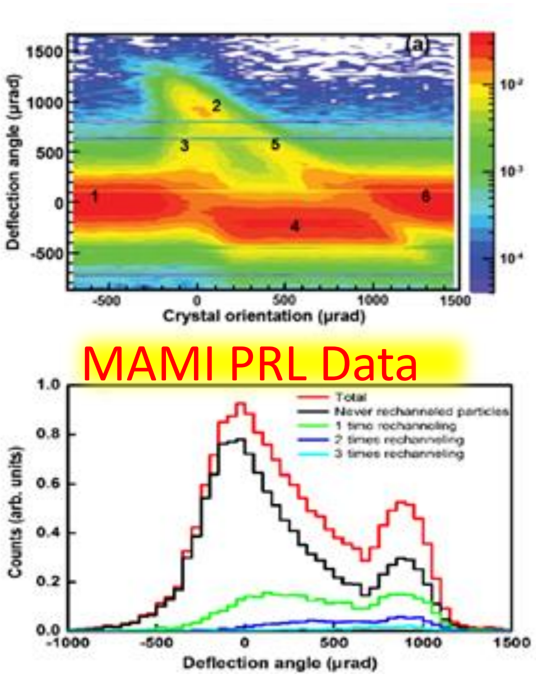
  → $\varepsilon'_{G4} = 1.5 \times (14.6 \pm 1.3)\% = (21.9 \pm 1.9)\%$ considering Rechanneling «by hand»
  - Rechanneling is not negligible, if not decisive, only for the negative charges.

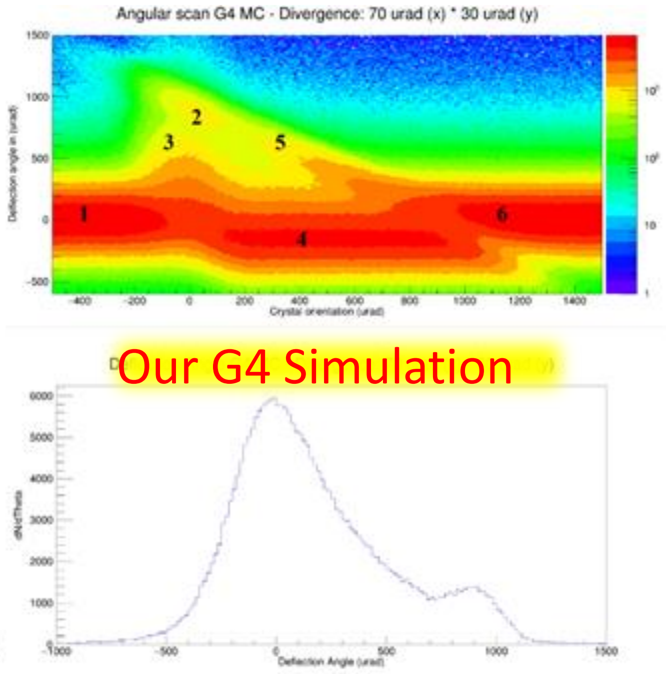
$\varepsilon_{Mami,Exp} = (20.1 \pm 1.2)\%;$

$\varepsilon_{Mami,MC} = 21.2\%$
(with Rechanneling)

Fair Agreement with ε'_{G4}

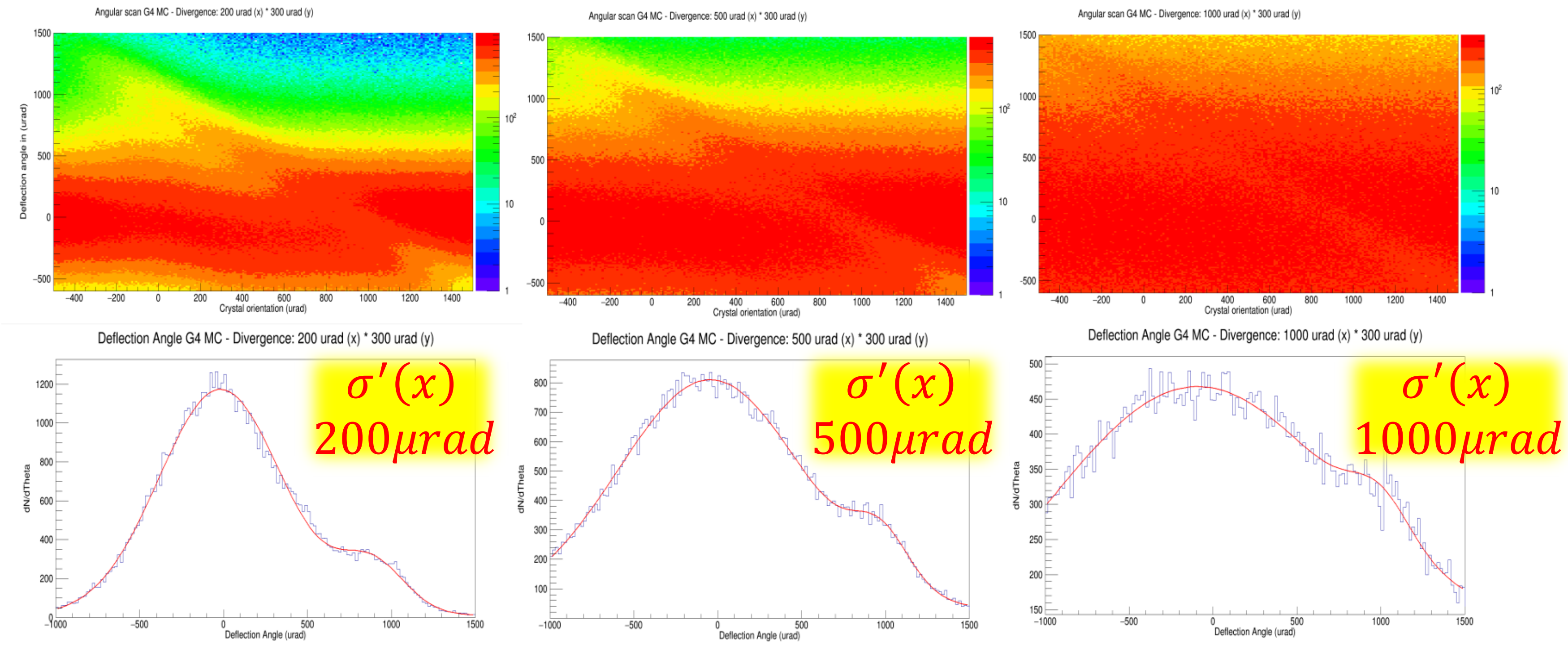






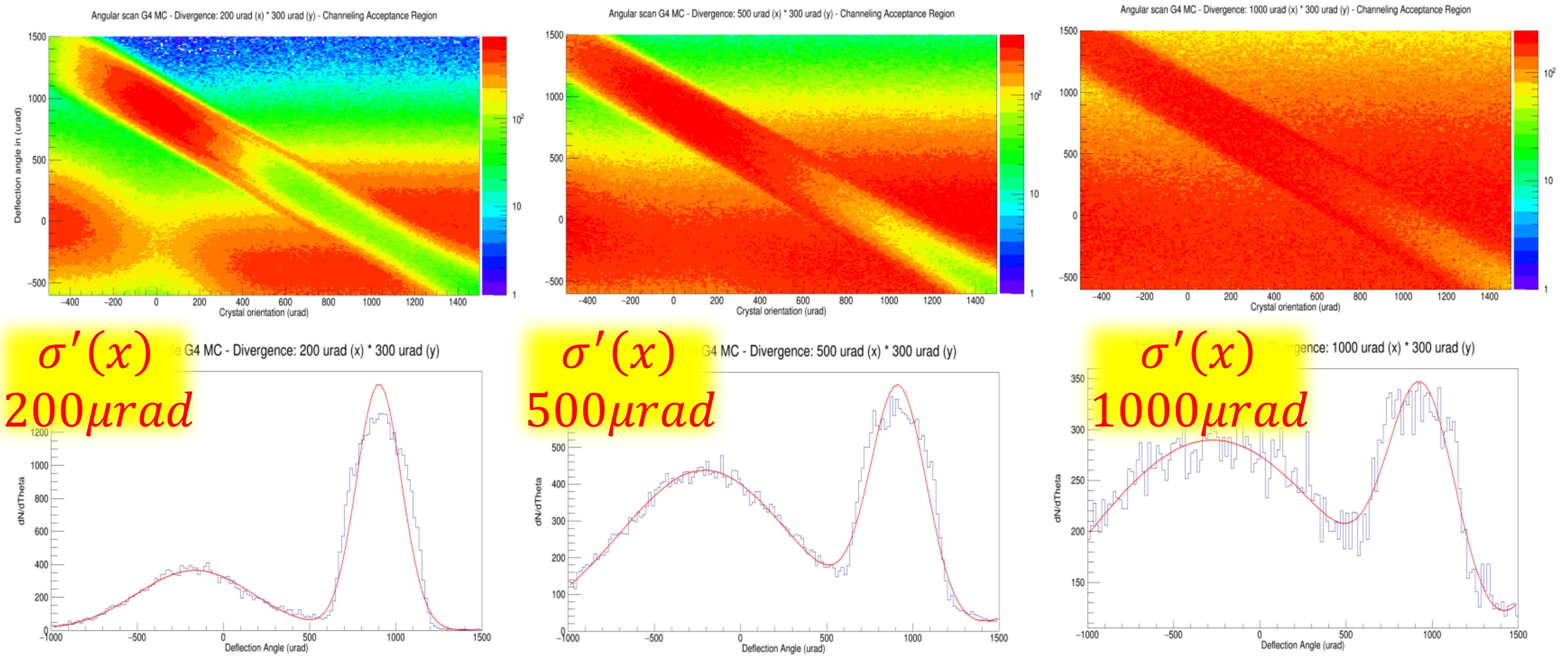
Geant4 INFN LNF BTF Simulations

- 511 MeV e^- simulations in the INFN LNF BTF setup
- It is necessary to disentangle the CH peak from the Background
  - Studies performed changing the $\sigma'(x)$ mantaining fixed $\sigma'(y) = 300\mu rad$
  - Angular Scan: MAMI-like procedure. G4 Simulations carried on (110) plane
  - Divergence $\sigma'(x) = 200,500,1000\mu rad$ in this slide



Geant4 INFN LNF BTF Simulations

- With e^- is hard to observe Channeling, so we decided to do also 511 MeV e^+ simulations in the same configuration. SHERPA needs e^+ extraction
  - Studies performed changing the $\sigma'(x)$ mantaining fixed $\sigma'(y) = 300\mu rad$
  - Angular Scan: MAMI-like procedure. G4 Simulations carried on (110) plane
  - Divergence $\sigma'(x) = 200,500,1000\mu rad$

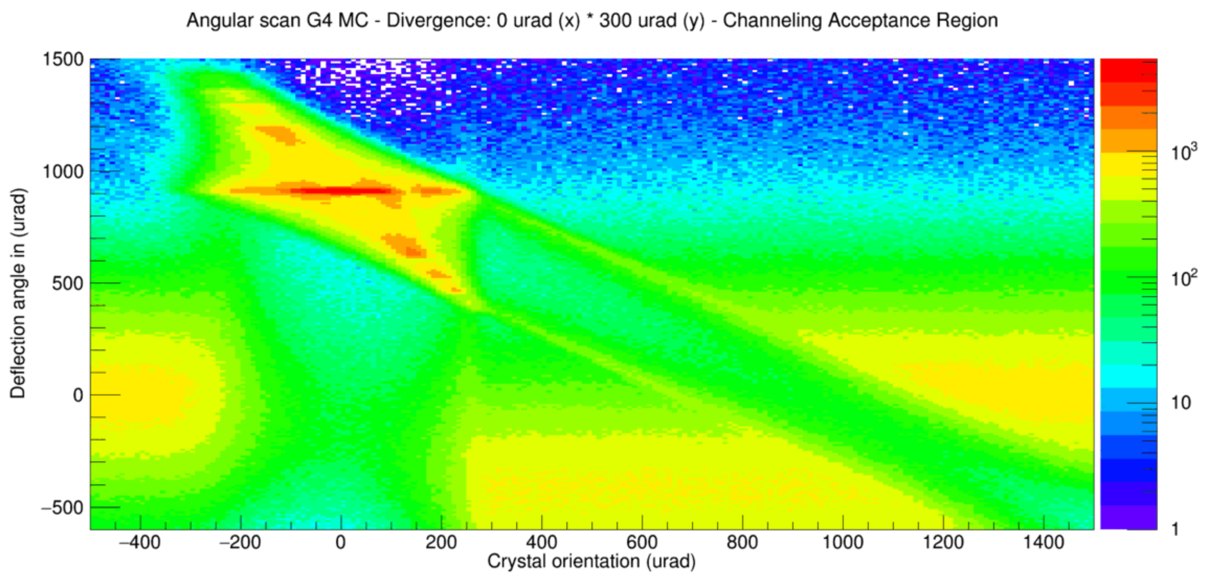


Backup

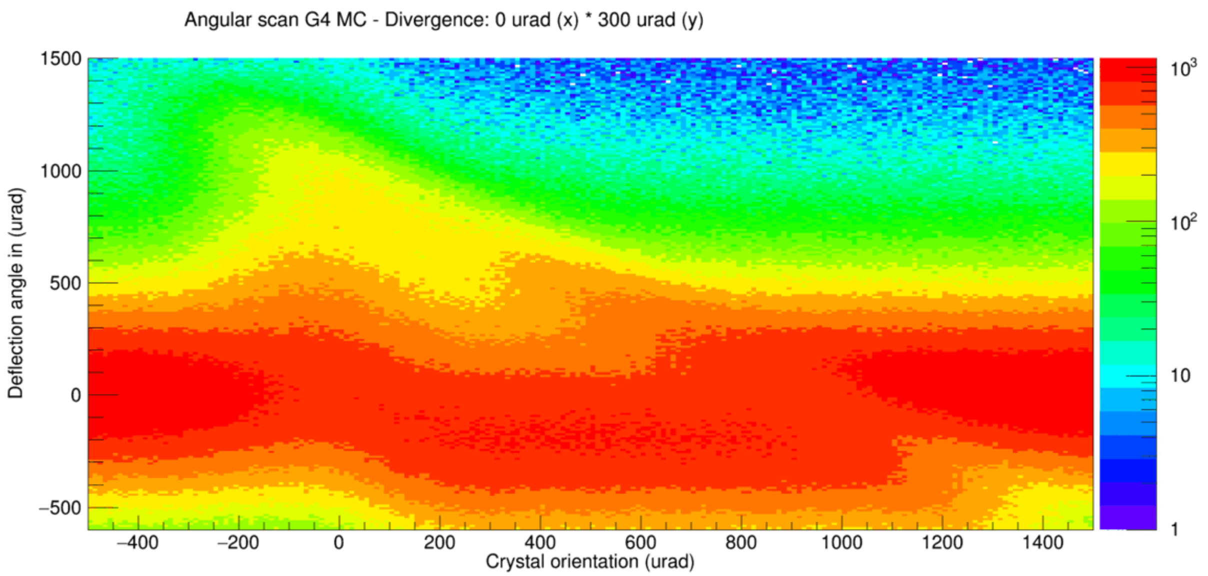
INFN LNF BTF 511 MeV e^+/e^- Simulations

- BTF SHERPA Geometry
  - Angular Scan: MAMI-like procedure. G4 Simulations carried on (110) plane
  - Spot RMS 1 mm^2
  - Divergence $\sigma'(x) = 0 \rightarrow 1000\ \mu rad$ and $\sigma'(y) = 300\ \mu rad$

- Positrons simulations



Electrons simulations

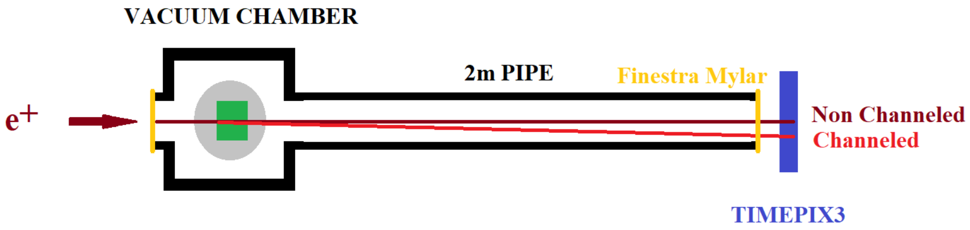


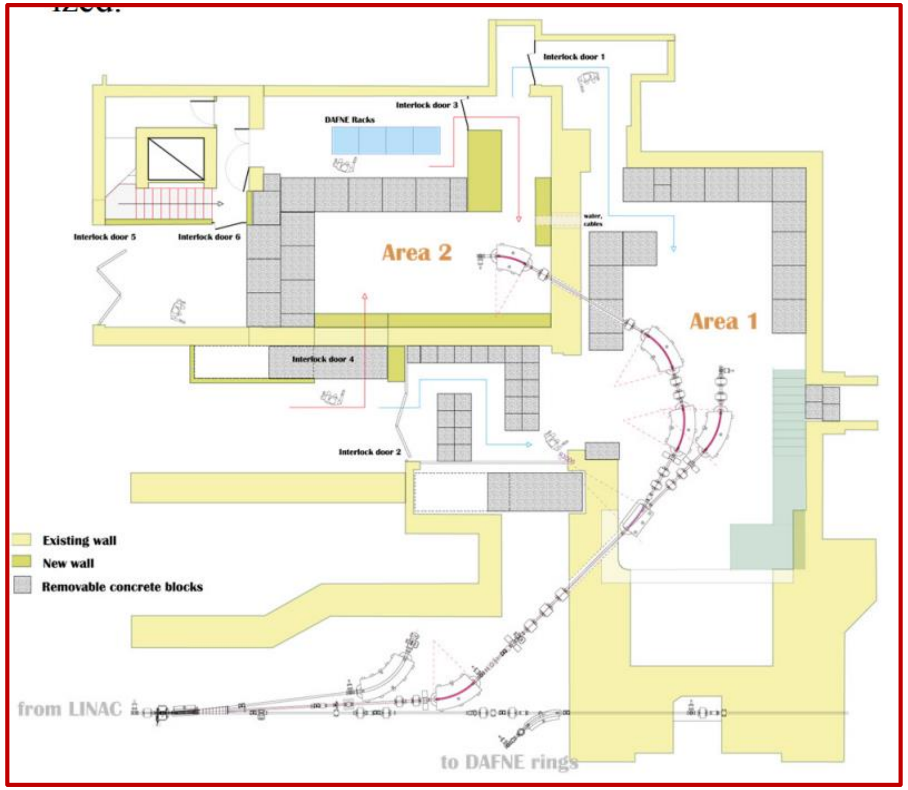
C SHERPA Simulations / Beam Spot

My Master Thesis

TimePix3 Beam Imaging Simulations

- SHERPA Pixel Si detector measuring the outgoing positions
  - Active surface of $14 \times 14\ cm^2$; 256×256 pixel matrix. $55\ \mu m$ pixel pitch
  - Thickness $100\ \mu m$
- Only e^+ impact position available at SHERPA TPX3
  - No information about incoming direction → No Anglular distribution
  - We evaluate positions, not angles
- Monte Carlo tailored to reproduce the Beam imaging in BTF-II
  - BTF-II free space of 3 m limits the SHERPA experimental setup
  - TPX3 placed 2/3 m downstream the crystal

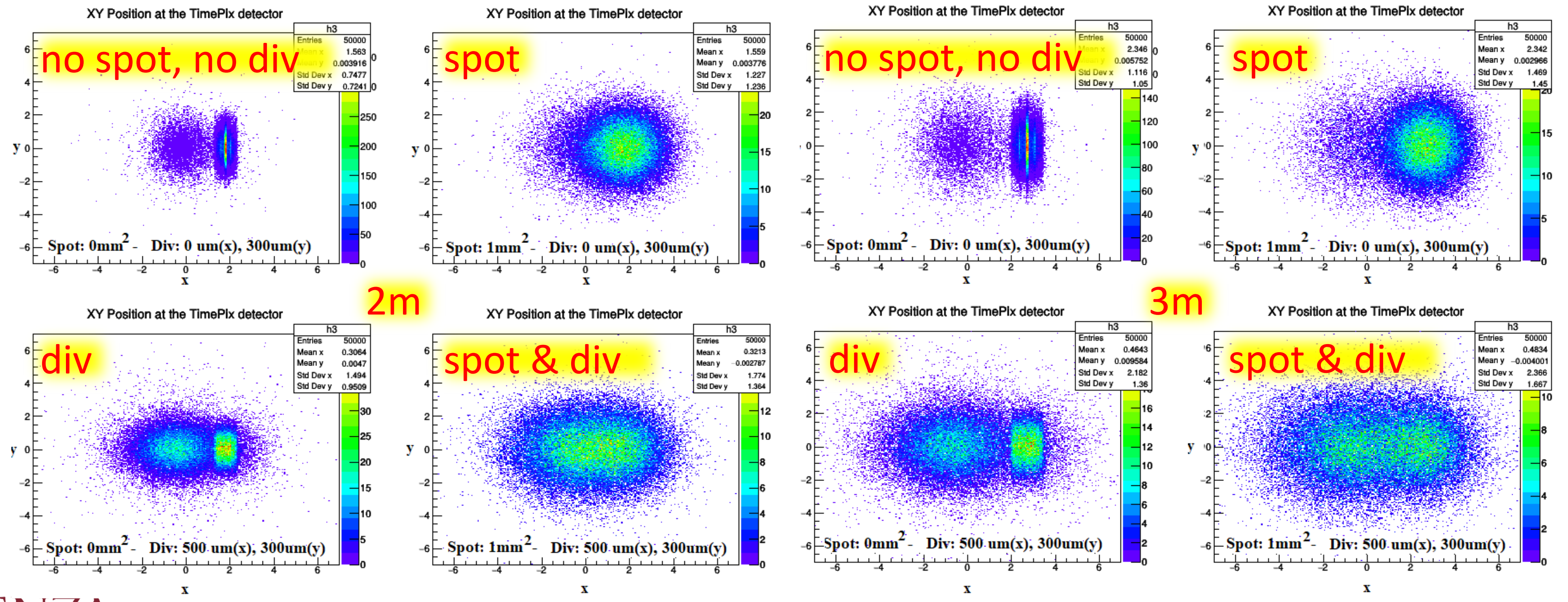




Backup

TimePix3 Beam Imaging Simulations

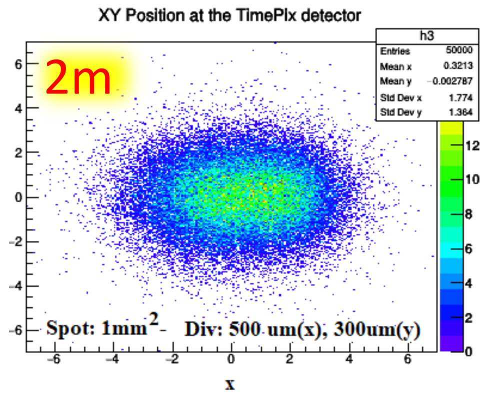
- Spot $\sigma(x) \times \sigma(y) = (0 \times 0)\ mm^2$ or $\sigma(x) \times \sigma(y) = (1 \times 1)\ mm^2$ RMS
- $\sigma'(x) = 0/500\mu rad$ (variable) and $\sigma'(y) = 300\mu rad$ (fixed)
- Detector distance: 2/3 m from crystal: Spot imaging (2D)
- Histo binning is chosen as the pixel pitch

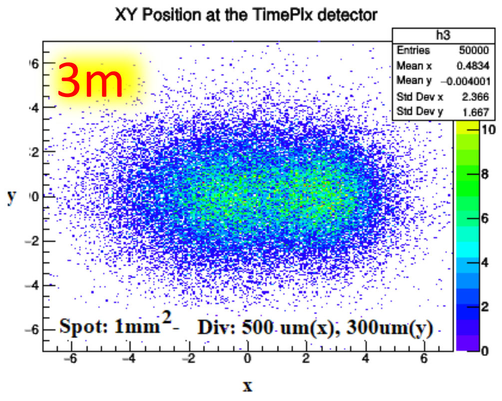


Backup

TimePix3 Preliminary Beam Indication

- Simulations performed with variable spot and divergence
  - $\sigma(x) \times \sigma(y) = (1 \times 1)\ mm^2$ and $\sigma'(x) = 500\mu rad$ - the Channeling is visible
  - PROBLEM: it isn't guaranteed BTF can reach $\sigma'(x) = 500\mu rad$
  - At 2 m the Channeling is not well separated. At 3 m it is better resolved





- As a first result, we proved that the spos should be sub-mm RMS radius
  - We think that the $\sigma(x) \times \sigma(y) = (0.5 \times 0.5)\ mm^2$ configuration is still achievable at BTF
  - Relaxing a little bit requirements on $\sigma'(x)$